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K. Gösele and S. Koch **

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1. INTRODUCTION

The determination of the loudness of noise has progressed so much during the last decade that the loudness can now be either calculated from a measured frequency distribution [1], [2], or it can be measured directly [3]. Therefore, it could be assumed that one has completely solved the problem of quantitatively characterizing noises with respect to hearing. However, general experience shows that it is not only the loudness which is important for the effect of disturbing noise on humans. Everyone probably agrees that a sine tone when applied for hours to a room has a much more disturbing influence than a wide band noise having the same loudness. In order to describe this effect, the concept of "bothersomeness" of a noise has been introduced which must be distinguished from its loudness.

Many experiments have been carried out to determine the bothersomeness of a noise and express it in numbers, in addition to determining the loudness. Most of the experiments, such as

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those carried out by Rademacher [4], Niese [5], Kryter [6], Zwicker [7] led to no unique determination of the bothersomeness in the case of continuous noise. Except for pulse sequences, the evaluation of the bothersomeness was always the same as the evaluation of loudness. Zwicker [8] therefore recently stated /325 one should no longer wait for a bothersomeness scale and one should use the loudness scale, which is already available.

It has been stated many times that the bothersomeness is a concept which is not defined enough, because it depends on so many psychological influences and coincidences. Therefore, one should not expect any direct relationships between the physical magnitudes associated with a noise and the bothersomeness.

In the following we will use a somewhat narrower concept, which we will call the "annoyance". By this we mean a measure for the human evaluation of continuous noise for continuous tones. The evaluation is restricted to cases in which there are no psychological effects. Essentially we wish to aid the practical acoustics researcher in answering an everyday problem. This is the problem of determining the effects of noises having different frequency compositions and different time sequences. For example these are the noises of traffic, industrial factories or neighbor apartments. These are the noises which human beings sense over long time periods.

In the following we will establish a method with which it is possible to describe this annoyance using hearing experiments. Apparently this can be done in a reproducible way. One finds that the evaluation is different from the loudness evaluation. The method is applied to the treatment of a special problem, the annoyance of band pass noise of varying frequency bandwidths.

2. MEASUREMENT METHOD

The contradiction between practical experience and the negative results of the already mentioned numerous experiments for establishing the bothersomeness component [4, 5, 6, 7] can only be explained by the fact that the test conditions in the mentioned experiments did not coincide with the conditions used to collect practical experience. Two deviations are remarkable: the effective time duration of the noise and the spatial conditions were different. In order to perform accurate experiments and in order to provide reproducible conditions, loudness comparisons were carried out for short signals which lasted about one second in a free acoustic field or with earphones. It is apparent that the concept of bothersomeness of a noise is closely related with a long duration of the noise. A noise which lasts only one second cannot have a bothersome effect, if we exclude a possible surprise or scaring effect, which did not occur in these experiments. Therefore, it seems that one of the first requirements for annoyance experiments is that the noise being evaluated should have a long duration. Whether or not the disturbing sensation is influenced by whether the noise exposure occurs in a free acoustic field or in a diffuse acoustic field cannot be evaluated immediately. In the experiments carried out, we also consider this possible influence.

A large number of test persons, usually between 10 to 15 persons, and sometimes even 50 persons were exposed to the noise in the form of a continuous noise lasting between 1/4 to 1/2 hour. The experiments were carried out in normal rooms with volumes between 50 m^3 and 500 m^3, and the reverberation times vary between 1/2 and 1 second. The acoustic pressure level at the location of the test persons was about 70 dB. This noise was interrupted

once in a while for a short time, and two times a comparison noise was introduced for 1 second to 2 seconds, twice separated by a short time interval. Figure 1 shows a schematic representation. The level intensity of the comparison noise was varied. The test persons had to decide whether they were more annoyed by the constant noise or by the comparison noise. The result was entered in a table. The sound was radiated at various level values, classified according to ten intervals of 5 dB each. The high and low level values had a random time distribution. /326
The comparison noise consisted of a wide band noise with a width of about four octaves extending from 250 Hz to 4000 Hz. The frequency distribution is shown in Figure 2. The results were used to determine the acoustic level at which the long duration noise and the comparison noise were found to have the same annoyance. Figure 3 shows the evaluation for two examples. The average value was then found from the results of all the test persons. An acoustic level measurement arrangement which integrates over time and space (see [9]) was used to determine the values of the acoustic level and its frequency distribution near the test person in the room.

As a measure for the annoyance of a noise in the experiment, we introduce the annoyance level L_{St} (in dB). Numerically it is assumed to be the same as the acoustic level L_V in dB(A) of the test noise which in the described experiment will be sensed to have the same annoyance as the noise being evaluated. In order to have a direct comparison with the loudness evaluation, we also calculated the loudnesses of the long duration noise (Λ_D) and that of the comparison noise (Λ_V) determined to have the same annoyance. We then calculated the difference

$$\Delta\Lambda_S = \Lambda_V - \Lambda_D \qquad (1)$$

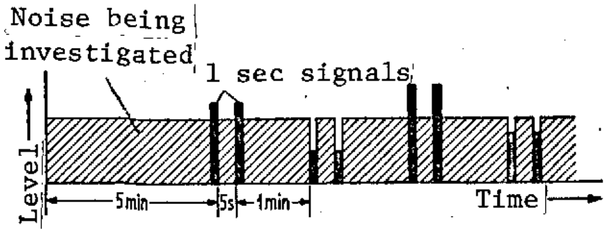

Figure 1. Time sequence during the experiments for determining the annoyance (schematic)

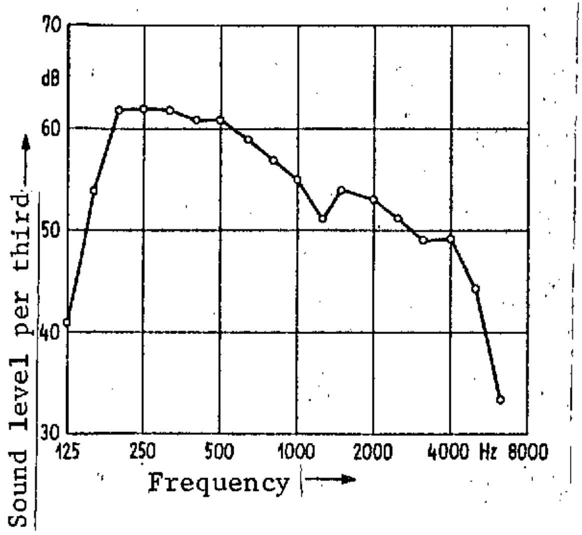

Figure 2. Frequency distribution for the wide band noise used in the experiments described in Figure 4

When sine tones were used, the loudness was determined according to equal loudness curves according to DIN 45 630 [10], and a correction for the diffuse field was applied, see for example [11] and [12]. The loudness of more or less wide band noise was calculated according to Zwicker [1] for the diffuse field [in phon (GD)] using third analyses.

3. TEST RESULTS WITH SINE TONES

One criterion for whether the method represents an advance is whether one would find an increased annoyance of sine tones compared with wide band noise, as dictated by experience. The first tests were therefore carried out with sine tones.

Unexpectedly, they confirmed our expectations. Figure 4 shows the frequency distribution of the evaluations of 49 persons on the annoyance of a 2.5 kHz sine tone. The abscissa is the difference $\Delta\Lambda_S$, that is the difference between the calculated loudness of the comparison noise and that of the sine tone, when both are sensed to have the same degree of annoyance. On the average, this difference amounted to 18 phon. The statement reliability of the "untrained" test persons is relatively high.

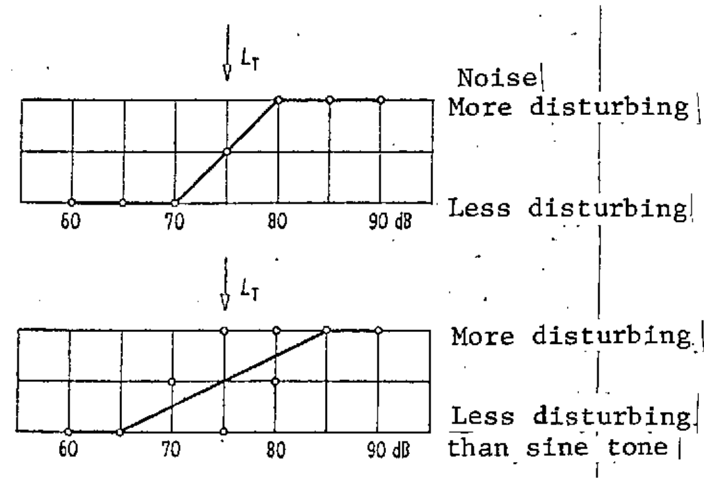

Figure 3. Examples for the evaluation of the opinions of test persons

Top: Test persons with decisive opinions
Low: Test persons with uncertain opinions

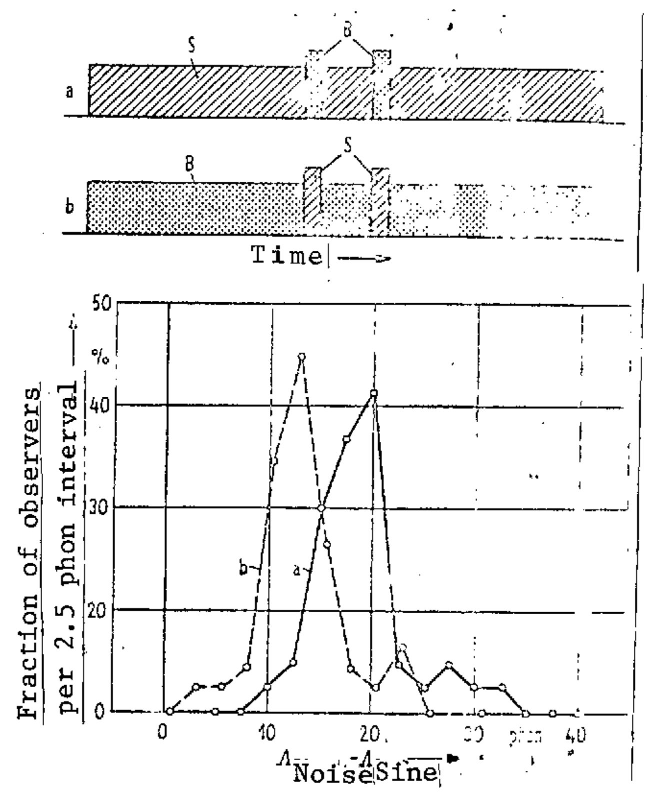

Figure 4. Frequency distribution of opinions of 49 and 45 test persons, respectively, as a function of the required sound intensity distance between wide band noise and 2.5 kHz sine zone, so that both are evaluated with the same annoyance

Curve a - sine tone S as continuous noise.
Curve b - wide band noise B as continuous noise

More than 80% of all the evaluations were within a ±5 dB range. Therefore, the obvious objection that such an experiment was too inaccurate because of the strong local scatter of the sine tone, did not apply. Numerous experiments in various rooms and with /327 various test persons continued to confirm this result.

4. CLASSIFICATION ATTEMPT

Psychologists objected to comparison experiments. In the present case such objections are especially appropriate because we are comparing two different things. We are comparing a long duration signal and a short signal. However, we were able to partially counter the objection of the influence of time, because the test persons surprisingly reached a similar conclusion when we used a wide band noise and a short duration interspersed sine tone comparison noise as the long duration noise, instead of the sine tone alone. According to Figure 4, it was found that the sine tone having the same amount of annoyance was 12 dB softer than the noise. In order to carry out a better comparison, Figure 4 shows not $\Delta\Lambda_S$, for this test result, but instead we have plotted $(\Lambda_{noise} - \Lambda_{sine})$. According to a suggestion of Hoermann and von Eiff [13], an attempt was made to compare the sine tone and the wide band noise for annoyance without a direct comparison. For this, the noise being evaluated was again used on the test persons in a normal room, at various level intervals of 5 dB between 50 dB and 90 dB, and the sequence of the intervals was completely random. The individual noise intervals were each offered for approximately one minute. The test persons had to classify the noise being evaluated according to the following evaluation stages:

1 Harmless
2 Small degree of annoyance
3 Annoying
4 Very annoying
5 Extremely annoying

If desired, they could also assign intermediate marks. The first group of test persons was first exposed to the sine tone and then they were exposed to the wide band noise in a later experiment.

In another test group, also consisting of between 10 and 15 persons, the order was reversed so as to compensate for a possible influence of the first experiment on the second experiment. However, it was found that there were no systematic influences. Figure 5 shows the results obtained for the three test groups. The abscissa is the loudness calculated from the acoustic level and the frequency distribution according to Zwicker [1]. The ordinate is the evaluation marks averaged over all of the test persons. First of all it is remarkable that the opinions of the different groups, however averaged over 10-15 persons, are remarkably close. Therefore it is possible to evaluate continuous noises in this way. Figure 6 shows an average from the results of the three test groups. The most important result is the fact that the sine tone and the noise were not found to have the same degree of annoyance for the same loudness. Instead, the same evaluation mark is reached when a sine tone is about 15 phon softer than a wide band noise. /328

Therefore, the evaluation according to the classification has given the same qualitative result as was found with the arrangement described in Section 2. The difference in the loudness of the noise and the sine tone which were found to have the same degree of annoyance was found to be 15 phon (GD) according to the classification. According to the comparison method of Section 2, this difference is 18 phon (GD).

If the evaluation of the noise and the evaluation of the sine tone are not plotted against their loudnesses but against their acoustic level, we find only a small difference in the

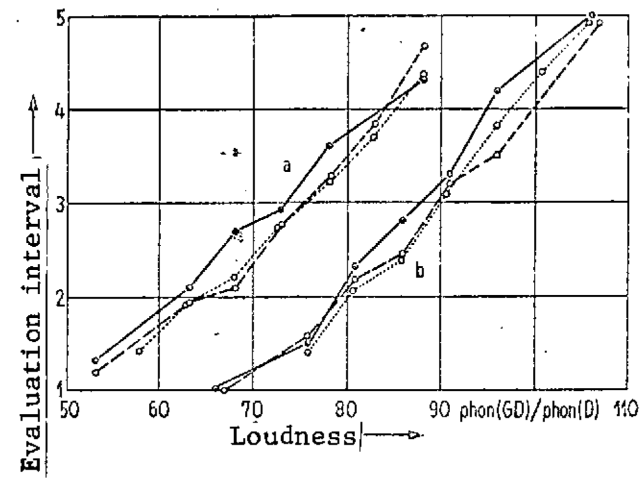

Figure 5. Classification of the annoyance of a 1-kHz sine tone (Curve a) and of a 4-octave wide band noise (Curve b) for various noise intensity levels in a room. Each experiment was carried out with three separate test groups of 15 observers each

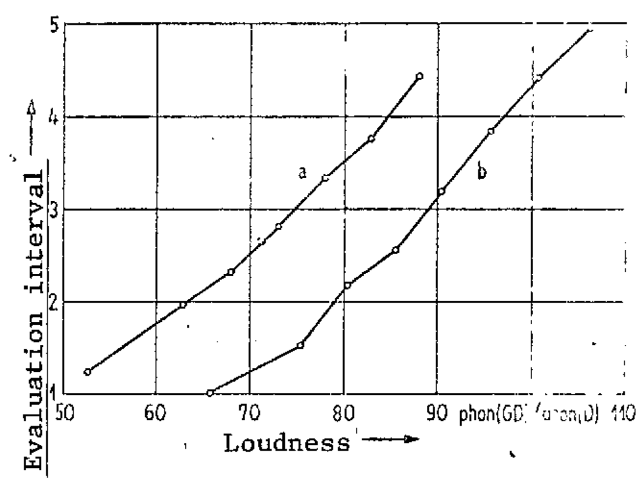

Figure 6. Classification of the annoyance of a 1000 Hz sine tone (Curve a) and of a 4-octave wide band noise (Curve b) for different loudness levels in a room. Average values for 45 test persons

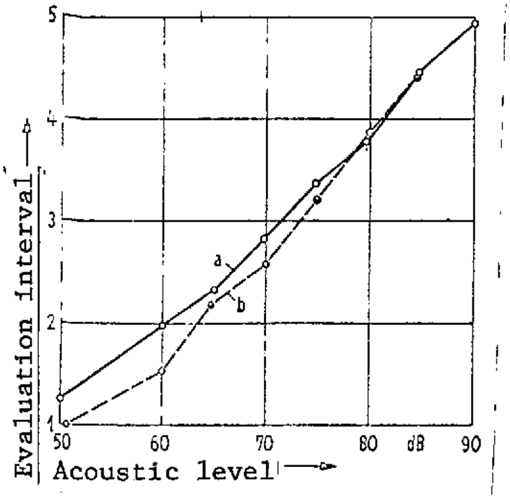

Figure 7. Classification of the annoyance of a 1000 Hz sine tone (Curve a) and of a 4-octave wide band noise (Curve b) for various values of the acoustic level in a room (values of Figure 6)

evaluation of the two noises. This can be seen in Figure 7. The difference amounts to only 2 dB to 3 dB. It is found that the sine tone is more annoying than the wide band noise for the same acoustic level.

5. THE INTERPRETATION OF EFFECT

Compared with the loudness comparison according to DIN 1318, the annoyance comparison differs in three respects. Differences occur in the time duration, the spatial conditions and the evaluation as to "annoying" or "loud". In the following we will discuss the individual influences using special experiments.

5.1. Time duration

In order to determine the importance of the time duration for the evaluation, earphones were used to carry out loudness comparisons between sine tones and wide band noise. The duration of each signal was changed widely. The details of the test conditions are shown in Figures 8 and 9. Figure 8 shows the loudness increase for a 1000 Hz tone, if instead of using the same time interval for the sine tone and the noise, the duration t_1 of the sine tone is increased. As could be expected according to investigations of Kryter [6], the loudness increases with the signal time duration. However, we did not find such a large increase as reported by Kryter. We found 4.5 dB increase when the time t_1 was increased. For very long times, we find that the overall increase is 8 dB.

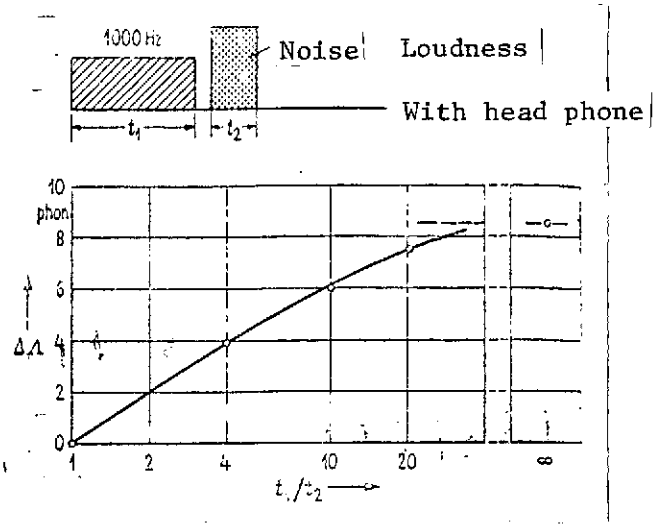

Figure 8. Increase ΔΛ of the loudness impression of a 1-kHz sine tone with increasing time duration t_1, compared with t_1 and t_2= 1 s

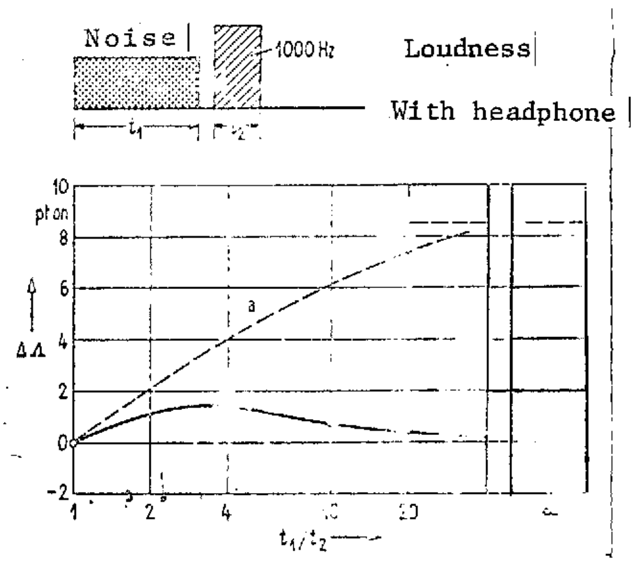

Figure 9. Increase ΔΛ of the loudness impression of a four octave wide band noise with increasing time duration t_1, referred to t_1 and t_2 = 1 s

Curve a: behavior of a sine tone, according to Figure 8, for comparison

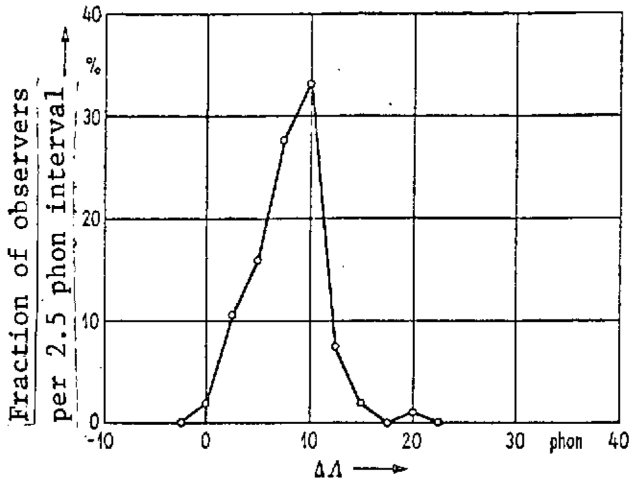

Figure 10. The influence of the room on the loudness comparison for short signals of 2.5 kHz sine tones and wide band noise. The curve shows the frequency distribution of the opinions of 47 persons. The abscissa ΔΛ gives the deviation of each opinion from the calculated loudness values. (Positive values: sine tone is found to be too loud)

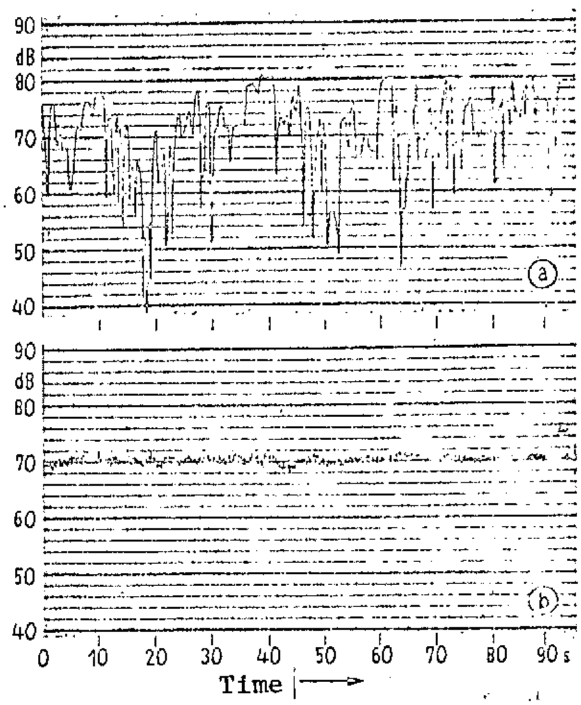

Figure 11. Time variation of the acoustic level at the ear of an observer in a room for a sine tone (a) and for a wide band noise (b)

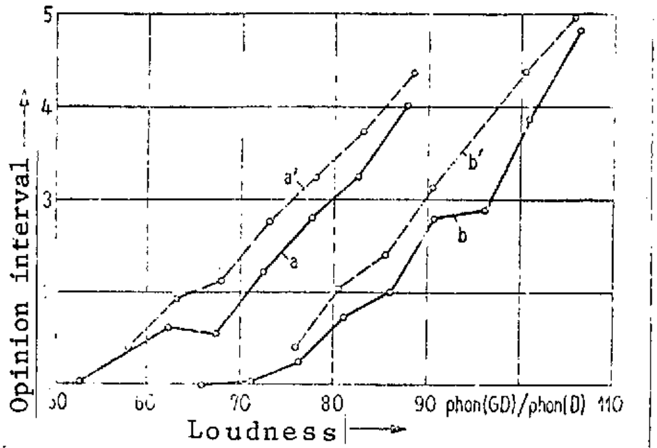

Figure 12. Classification of the loudness of a 1000 Hz sine tone (Curve a) and of a 4-octave wide band noise (Curve b) for different loudness levels in a room, average of 16 test persons

The curves a' and b' are the opinions of the same test persons for an annoyance evaluation

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If the same experiment is made with no noise, by varying the duration of the noise and holding the duration of the sine tone constant (see Figure 9), we find a different result. As shown in Figure 9 in this case the noise loudness almost does not increase in this case as the noise signal is made longer. The loudness impression therefore increases only for the sine tone and not for the noise. At this time we are not able to give an explanation for this result.

5.2. The influence of the room

Numerous loudness comparisons between a 1-kHz or a 2.5-kHz sine tone and wide band noise were made in rooms and both signals were applied about one second to two seconds. We found the consistent result that the loudness of a sine tone, compared with that of a wide band noise, was always larger in a room than when calculated according to Zwicker. Figure 10 shows the frequency distribution of the evaluations of 45 persons. The abscissa is the loudness increase for the 2.5-kHz sine tone compared with the computed value. The experiments were compared by pairs, and in one experiment the sine tone was held constant, and in the next experiment the noise was held constant. The loudness of a sine tone is therefore 10 dB higher on the average than according to the calculation.

What is the basis of this space influence? The acoustic level of a sine tone at the ear of an observer varies greatly in a room, as soon as he moves his head somewhat. Figure 11 shows the time variation of the level for a 1000 Hz sine tone and for a 4-octave band path noise, when the observer moves slowly. It is perhaps important that the phase difference between the two ears has considerable time fluctuations in the case of sine tones. One can attempt to demonstrate the influence of this effect on the loudness impression by carrying out loudness comparisons in the earphones, where the sine tone is transmitted stereophonically from the room. Experiments carried out did indeed show that there was a loudness increase.

5.3. Influence of the question posed

In addition to the influence mentioned, it can be important whether or not the test person was asked to determine "loudness" or "annoyance". Therefore we carried out different experiments during which a group asked to determine one of these qualities was then asked to determine the other one. The results are not completely uniform. As long as short signals were presented, the type of question posed is not important. As soon as the sine tone is maintained continuously in a room, it is evaluated more unfavorably when the annoyance level is requested. In this /330 connection it is important to consider the result of an experiment described in Section 4. For this a test group of 15 persons was used which had not yet performed any acoustic comparison experiments. In this way we wanted to avoid any prejudice because of earlier experiments. Just like in the tests described in Section 4, this group was first offered a 1000 Hz sine tone and later on a wide band noise as a continuous noise and at various level intervals. The test persons were asked to evaluate the "loudness" according to five prescribed evaluation marks

1 Quiet
2 Not so loud
3 Loud
4 Very loud
5 Extremely loud

Figure 12 shows the average evaluation of the test persons. The evaluation mark for one level interval each is shown as a function of loudness. As already discussed in Section 4, this was calculated according to DIN 45 631 from the measured acoustic level values, as described by Zwicker [1]. The evaluations determined in this way are very different from the ones determined by calculation. The sine tone appears to the test persons to be approximately 15 phon louder than what is obtained from calculation assuming wide band noise of the same loudness. The evaluation of the loudness of the sine tone and of the noise by the test persons again would approximately coincide if instead of the calculated loudness we would use the acoustic level as the abscissa.

After a long rest, the test persons were asked to evaluate the annoyance. The results are shown as the lines a' and b' in Figure 11. It can be seen that the evaluation overall is somewhat harsher and that the difference between the evaluations of the sine tone and the wide band noise has remained approximately the same as for the loudness evaluation.

Summarizing we may say that the various experiments show that there are two essential reasons for the difference between the loudness comparison and the evaluation of a sine tone using the method of Section 2. About 8 dB can be attributed to the influence of time (continuous tone, instead of short duration signal). About 7 dB can be attributed to the influence of the room, and probably the large time and space variations of the level are important for the sine tone. Apparently it is not important whether the test persons were asked to determine "loudness" or "bothersomeness" or "annoyance", respectively. Overall we have the impression that the discrepancy between practical experience and loudness mentioned at the beginning of this article can be attributed less to the difference between "loudness" and "annoyance". Instead it must be attributed to the different nature of the effect of the sound when it is propagated in a normal room and at the same time lasts for a long time, instead of when short signals are radiated in a free sound field. Perhaps it is necessary to use a modified loudness concept for continuous noise instead of the concept of annoyance in order to interpret the phenomena.

6. ANNOYANCE OF NOISE WITH DIFFERENT FREQUENCY BANDWIDTH

According to the method given in Section 2 we investigated the annoyance of noise having different frequency band widths. The noise to be evaluated was imposed on a test group of between 10 to 15 male test persons (ages 16 to 18 years) in a 128 m^3 room with an average reverberation time of about 0.5 seconds. The tests were carried out with several groups. The noise had a bandwidth of 1/10 octave up to 4 octaves. The central frequency was 1000 Hz. In addition we also investigated a sine tone at the mentioned frequency. A four octave wide band noise was used for a short duration comparison noise, and its acoustic level had been found to characterize the annoyance when comparison noise and continuous noise had been evaluated to have the same degree of annoyance.

The frequency distribution of several noises evaluated to have the same degree of annoyance using this method is shown in Figure 13. /331

In Figure 14, Curve a represents the annoyance level L_{St} for various noises having the same loudness Λ_D calculated according to Zwicker [1]. Since the noises did not have the same loudness during the measurement, the values were recalculated for the same loudness and it was assumed that within the small range of variation, a change in Λ_D would correspond to the same change in L_{St}.

Figure 14 shows that noise with the same loudness does not have the same annoyance according to this method. The smaller the bandwidth, the more annoying will be the effect of the noise according to these results. This is most pronounced for the sine tone where the deviation of L_{St} compared with the 4 octave wide band noise with the same loudness amounts to 17 dB.

In this case we can also perhaps raise the objection that it may be a time effect. This is why the time durations for the narrow band noise and the comparison noise were exchanged, as is shown in Figure 14 for the Case b. The annoyance level* is found to be lower than for Experiment a. The difference between a and b is shown in Figure 15. For bandwidths up to 3 octaves, it amounts to about 6 dB. The basic variation of the Curves a and b

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* According to definition in Section 2, we are no longer dealing with an annoyance level. Nevertheless, this expression is used for the acoustic level of the four octave wide band noise for Case b, for clarity.

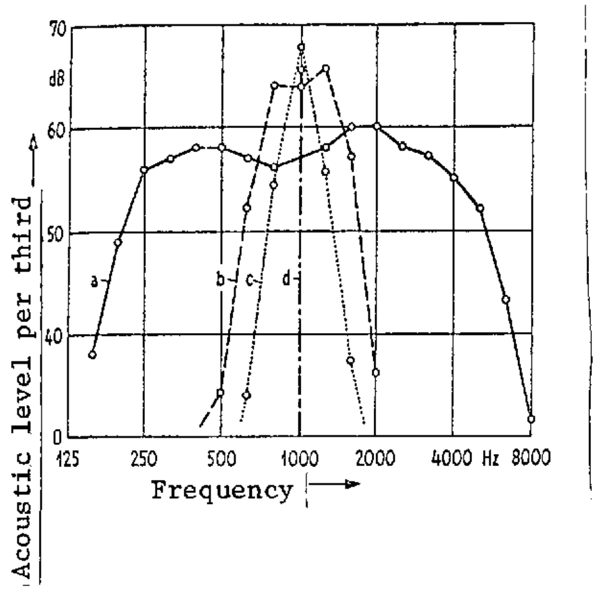

Figure 13. Frequency distribution of several noises sensed to to have the same annoyance

Curve a: 4-octave noise; Curve b: 1-octave noise, Curve c: 1-third noise, Curve d: sine tone

is similar, however, in other words there is an increase annoyance level in the case of narrow band noise. Finally, Curve c in Figure 14 shows an average value for the results of Experiments a and b. The value of 14 dB obtained for the sine tone corresponds quite well to the value which was determined using the classification of sine tones according to the method given in Section 4.

Since the experiments showed that the annoyance of such noise is not in agreement with the loudness, in Figure 14 we did not use the loudness as a parameter but instead the acoustic level in dB(A). The curve in Figure 16 shows that the annoyance level L_{St} hardly depends on the bandwidth of the noise at all,

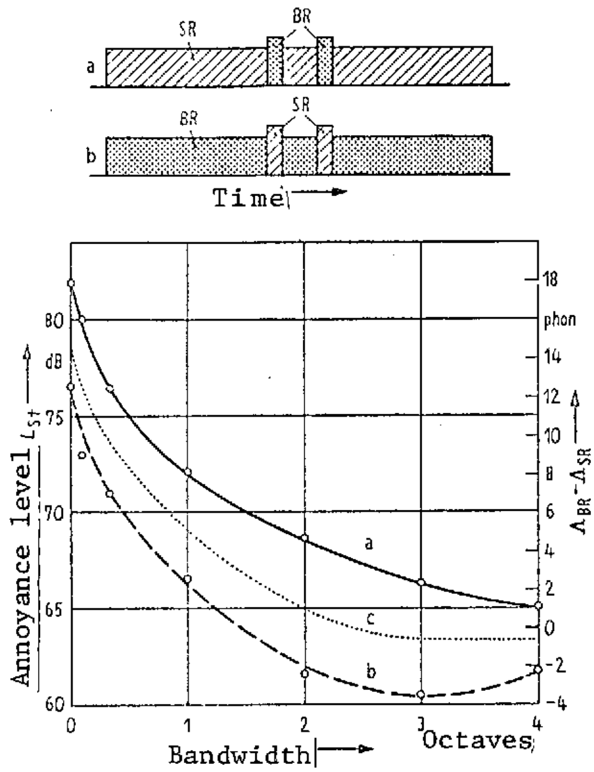

Figure 14. Annoyance level L_{St} for noise with the same loudness at various bandwidths (or for sine tone respectively)

Curves a and b: for the test installations a and b discussed above, Curve c: average value of experiment a and b. BR: wide band noise. SR: narrow band noise. Constant loudness Λ_D = 80 phon (GD)

except for the sine tone for which L_{St} is about 4 dB higher than /332 for the noises. The same is true when we consider the average value of the experiments a and b shown in Figure 14, which is shown in Figure 16 as Curve c.

These experimental results do not contradict previous experience entirely.

Wells and Blazier [14] also carried out experiments on bothersomeness of bandpass noise having different frequency band widths. However, the method described at the beginning of this article was not used. The results agree with our to the extent that for a noise with a band width of 1/3, one does not obtain the value expected according to the loudness. Instead one obtains a value which is about 20 dB higher compared with a 25 third wide noise.

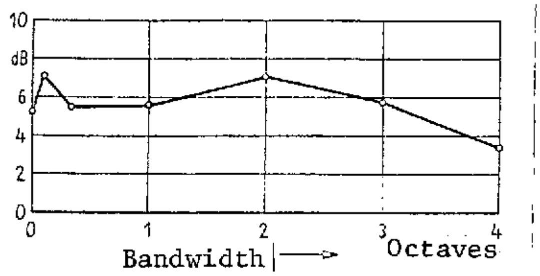

Figure 15. Difference of the annoyance level L_{St} between experiments a and b in Figure 14, as a function of the noise band widths

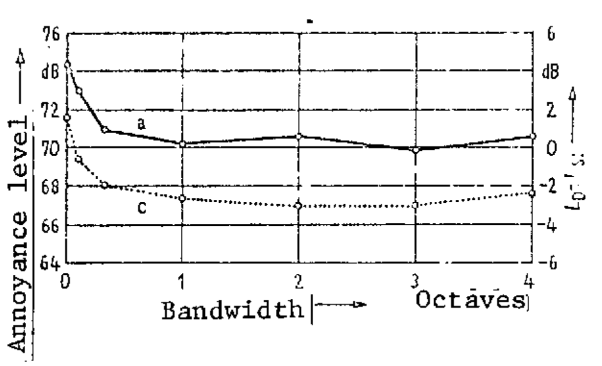

Figure 16. Annoyance level L_{St} for the noise of various bandwidths (or sine tone respectively) for the same noise level L_D and for the test installation a described in Figure 14, as well as for the average value of a and b (Curve c)
Constant noise level L_D= 70dB(A)

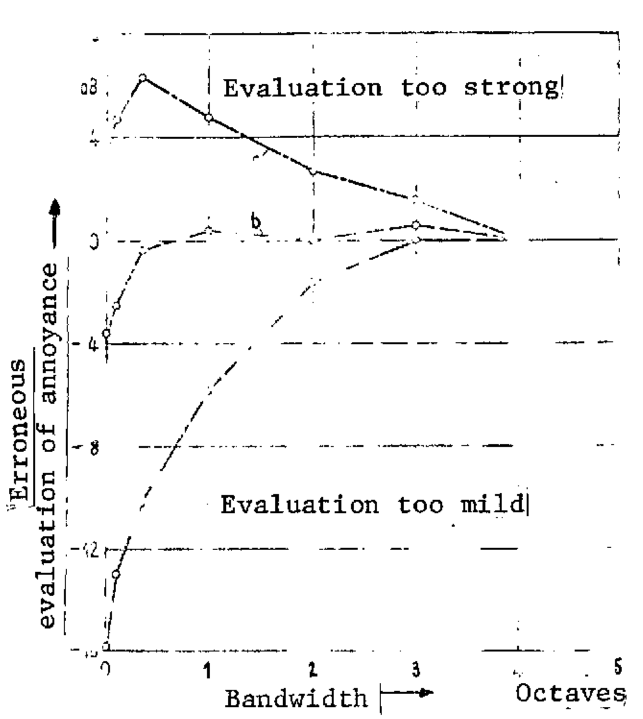

Figure 17. Erroneous evaluation of the annoyance of bandpass noise with various bandwidths according to different evaluation methods

Curve a: according to loudness (calculated according to Zwicker), Curve b: according to the noise level in dB(A), Curve c: according to the limiting curve method (Evaluation of the third spectrum according to noise rating curves). Evaluation for 4-octave wide band noise always set = 0

7. CONSEQUENCES FOR THE NOISE EVALUATION

In order to evaluate noise we have three different methods available.

a: Evaluation according to loudness

b: Evaluation according to a frequency-weighted acoustic level,

c: Evaluation according to limiting curves [15], [16].

The evaluation according to perceived noise level in PNdB according to Kryter [17] is a modification of Method a, and different frequency curves are used.

The methods a to c essentially differ in the way the energy contributions of the individual frequency ranges of a wide band noise are summed. In the case of the loudness we have a very strong addition according to the (attenuated) loudnesses. In the case of the acoustic level we have an addition according to energy. In the case of the limiting curve method only the highest level of one third or octave is important after a certain frequency weighting, and no summation is carried out. The frequency weighting used in the three methods is also different in each case. This difference, however, is not as great as the difference in the type of summation. Up to the present, no decision has been made regarding the usefulness of the three methods for practical evaluation of industry, noise and similar noise. The experiments described here will help to make this decision.

For this purpose we evaluated the noises with different frequency bandwidths (see also Figures 13 and 14), which had been found to have the same degree of annoyance, according to the three methods.

Since the absolute value of the evaluation is not important, we referred everything to the value for the 4-octave noise. This value was set equal to zero for all three methods. Since noises having the same degree of annoyance were considered, any deviation from the value of zero according to each method must be considered as an erroneous evaluation of the annoyance. /333
Figure 17 shows the calculated values. We find the result that the limiting curve methods evaluate the narrow band noises and the sine tones too harshly compared with the evaluation of the wide band noise. The loudness, conversely, results in an evaluation which is too mild. On the other hand, the annoyance is correctly evaluated by the acoustic level in dB(A), except for the sine tone, which is evaluated too mildly by 4 dB(A)

Based on these results one can assume that industrial noises and other disturbing long duration noises are better evaluated according to dB(A) than according to the loudness or according to the limiting curve method. The erroneous evaluation for prevailing sine tones which still exists can be reduced by adding a value to the measured value in dB(A). This increment does not have to amount to more than 4 dB. This statement first holds for wide band noise which does not contain a large number of individual tones. We will write a special report on such noise.

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16. Abstract

To determine its annoyance, the noise to be tested was presented in furnished rooms in form of a permanent noise. This permanent noise was compared with inserted signals of broadband noise. The experimental results have demonstrated that the weighted sound pressure level and not the loudness level is representative of the annoyance. The discrepancy found by judging noise according to the loudness level is caused by the influence of room configuration and noise duration (short signals or permanent noise). Experimental results have shown that the judgment of noises according to the Noise Rating Curves corresponds less to the subjective impression than the judgment based on the sound pressure level.

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